Game Changer Technologies for Optical Systems and Disruptive Innovations for Remote Sensing Systems

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15/11/2018
The ESA Earth Observation Φ-week

From Applications Pull to Technology Push

Design to cost

- *Simple to use ➔ a-thermal design*
- *Easy to assemble ➔ minimize the number of components*
- *Modular design ➔ all reflective elements*
- *Use of COTS for EEE & Detector ➔ switch from CCD to CMOS*

Enabling Technologies

- *RSP Aluminum Alloys* → Higher strength and stiffness
  Lower CTE
  Higher Temp strength and wear resistance
- *Free form design tools*
- *Single Point Diamond Turning*
- *Free form precision metrology*

Free form components!

- ❑ Compact design
- ❑ Good image quality
- ❑ Big field of view
- ❑ Good throughput

Two main areas of applications for Compact Optical Payloads

Land/ocean observations:

- All-reflective with freeform mirrors
- Spectral separation with Linear Variable Filter (LVF)
- Area array detector (instead of a multi-linear array)

Atmosphere observations:

Full-reflective Grating Spectrometers:

- Free form grating and only two spherical mirrors (eg. ELOIS)
- Free form mirrors and flat grating (eg. TROPOLITE)

Development of Optical Payloads in ESA/TEC

Existing Payloads (flying or ready to):

For minisatellite platforms

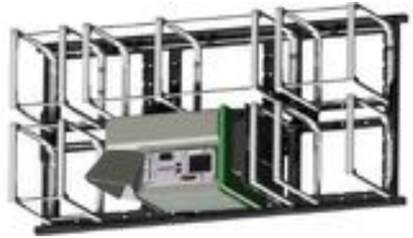
STREEGO

Proba V

For cubesat platforms

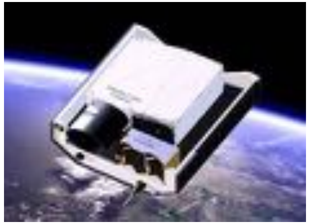
HyperScout

PFM HyperScout IOD



Planned Payloads:

HyperSTREEGO



CHIEM

ELOIS

CHIMA

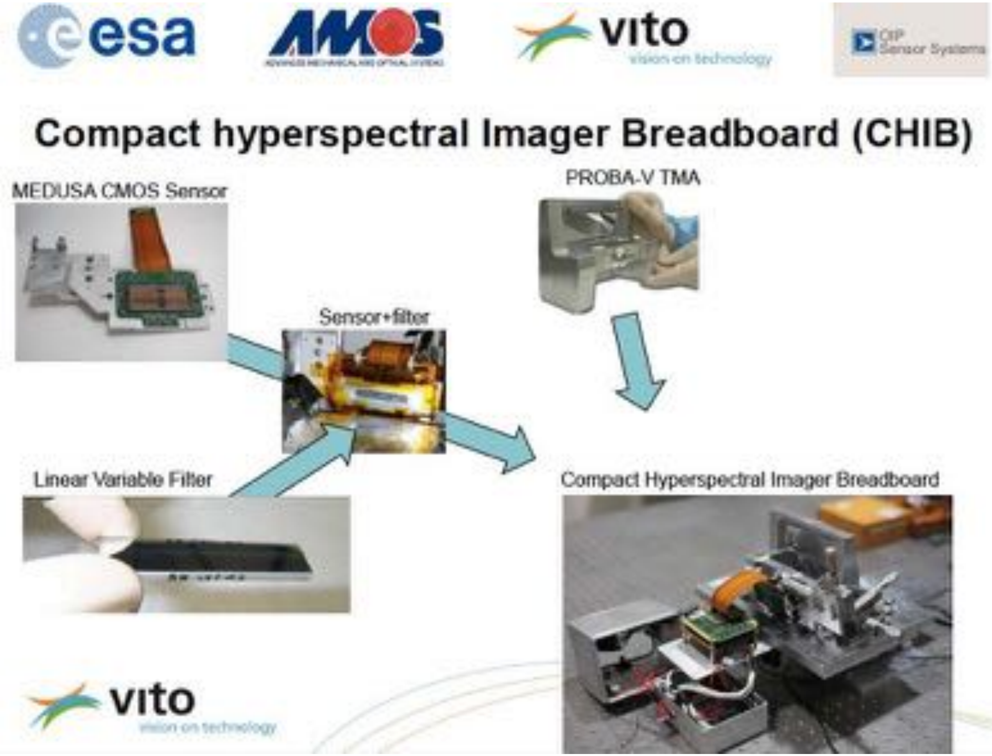
(land/ocean)
(atmosphere)

From Multi- to Hyperspectral, from Mini- to Cubesat

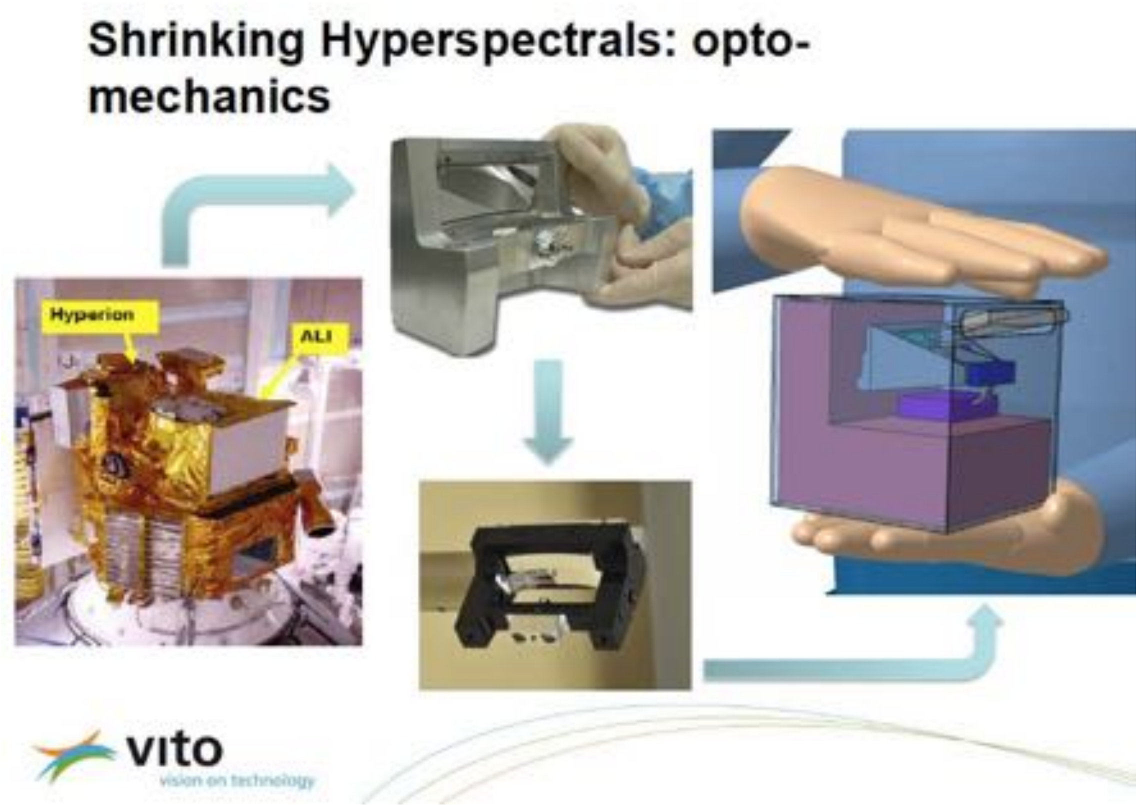
The idea to go from Multispectral to Hyperspectral started during the 'early days of Proba-V'

The 1st SoW on Hyperspectral release by the European Space Agency was:

"Compact Hyperspectral Imager Breadboard" (CHIB), July 2009, ITT for 200K€



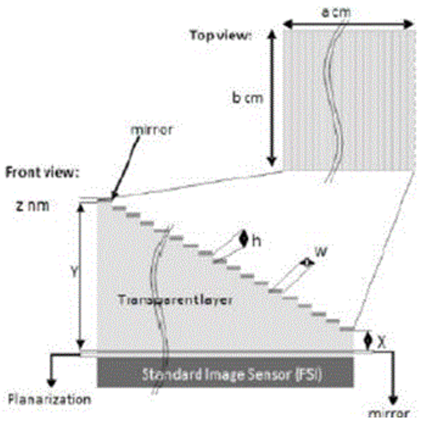
Hyperspectrals in cubesize - optics

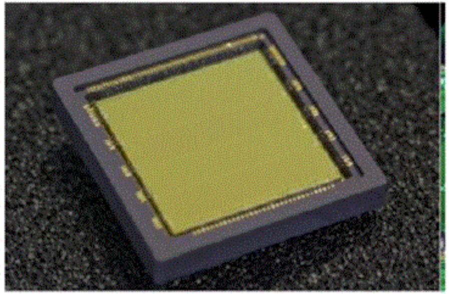


The "HyperCube"!

a hyperspectral instrument in a CubeSat was presented at Small Satellite Conference in UTAH in <u>August 2011</u>

Hyperspectrals in cubesize – dispersion with LFV





The principle of the **Linear Variable Filter**:

- Hyperspectral sensor done with Fabry-Perot filters post-processed on top of CMOS imager.
- Filter performance can be tuned to match the wanted requirements
- Filter perfectly aligned with sensor pixels
- No space between sensor and filter

Really, hyperspectrals in cubesize…?

The Signal to Noise Ratio and the spectral resolution are **low** when compared to traditional (and bigger) instruments.

1. Is there any application where a not so performing but very compact and cheap hyperspectral can deliver interesting measurements?
2. Is there any mission that could be interested in flying a tiny hyperspectral?

The answer to both questions was… **'NO'**

Hyperspectral in a cubesat: **HyperScout®**

✓ ***Technology push***: availability of all components
✓ Need to ***overcome downlink limitations*** for nanosats

➡ on-board data handling system for real-time L2 image processing

Highlights:

- Compact opto-mechanical system: **1.2 Kg** / 1.2 liter
- Large Field of View (**31° ACT x 16° ALT**): 80 m GSD @ 600 km orbit
- Works in 450 – 900nm, spectral resolution ~ 15nm
- **SNR >50**

cosine

TUDelft

imec vito

ISIS s[&]t

Target Applications:

➢ Vegetation condition (eg. NDVI)
➢ Crop water requirement
➢ Fire Hazard
➢ Flooding areas delineation
➢ Change detection of land cover and land usage

An example of application

pagamenti in agricoltura, utilizzando anche droni e satelliti, a censire, con precisione scientifica, i danni subiti dai boschi di larici e abeti dell'Altopiano di Asiago.

(..using also drones <u>and satellites</u> to conduct a census, with scientific precision, of the damages experienced by the woods of Asiago upland…)

MALTEMPO

Strage di alberi ad Asiago, summit dei sindaci: droni per contare il legno

La Regione pensa ad una commercializzazione «programmata» del legno

di **Redazione Online**

Pan ad Asiago

ASIAGO (Vicenza) «Sarà l'Agenzia regionale per i pagamenti in agricoltura, utilizzando anche droni e satelliti, a censire, con precisione scientifica, i danni subiti dai boschi di larici e abeti dell'Altopiano di Asiago. Le prime stime dicono che la tempesta di fine ottobre che si è abbattuta sul Veneto abbia lasciato a terra dai 300 ai 400 mila metri cubi di legname». La promessa arriva dall'assessore regionale all'agricoltura del Veneto, Giuseppe Pan, è salito oggi sull'Altopiano per rendersi conto di persona dei danni inferti al patrimonio boschivo e all'agricoltura di montagna dal maltempo e per incontrare nella sede della Spettabile Reggenza

HyperScout In-Orbit Demonstration - status

KO for HyperScout EM:	April 2014
HyperScout PFM delivery:	February 2017

- Platform: 6-U cubesat platform Gomx-4B (Gomspace, DK) at 500 km orbit
- Swath = 220 km, GSD = 70 m

February 2nd 2018: Gomx-4B launched with "Long March 2" Chinese rocket.

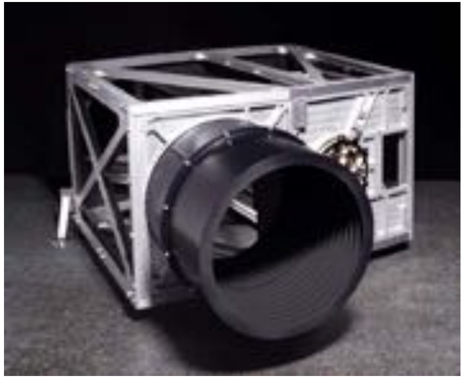
- First commissioning of core subsystems in March 2018:
  - **"First light":** a single frame with footprint of 200 x 150 km^2, binned 2x2 (to fit 1.5 MB data volume budget constrain)
  - House keeping data collected
  - All logs collected
- Full commissioning finalized in July 2018 (downsized hyperspectral datacube acquired)
- IOD operations ongoing to be finalized by end of 2018

Multi/hyperspectral in a minisat: **STREEGO**

→ modular pan/multi (/hyper)-spectral instrument for small platforms
→ medium-high spatial resolution

Highlights:

- Swath: 11 Km (20Km option) @ 600 Km orbit
- Panchromatic: 2.7 m GSD @ 600 km orbit
- Multispectral filters: 5.5 m GSD @ 600 km orbit 9 bands in 430 - 880 nm
- Upgradable to Hyperspectral (with LFV)
- Mass / Volume **19 kg / ~0.3x0.5x0.5 m³**
- Athermal system (RSA443 Al)

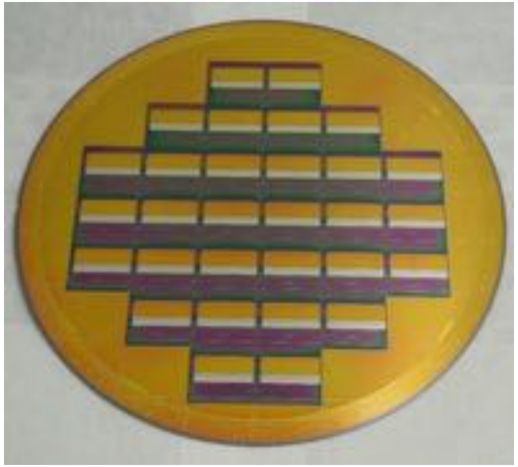


Target Applications:

- ➢ Agriculture
- ➢ Infrastructure Development
- ➢ Disaster Monitoring
- ➢ Surveillance
- ➢ Topography

Hyperspectral in a minisat: **CHIEM**

- ✓ Two wedge filters (LVF) directly deposited on CMOSIS CMV12000 detector at wafer level
- ✓ LVF on FSI CMOS and also on BSI CMOS (higher SNR, new development)
- ✓ Spectral resolution <10 nm
- ✓ Ad-hoc Readout Electronics manufactured and tested
- ✓ EM, including Front optics (TMA), designed and built (volume 300 x 200 x 130 mm^3)
- ✓ 2 LVF on FSI CMOS and 1 LVF on BSI CMOS characterised.



Deposition on Back Side Illuminated:

Wafers with filters deposited

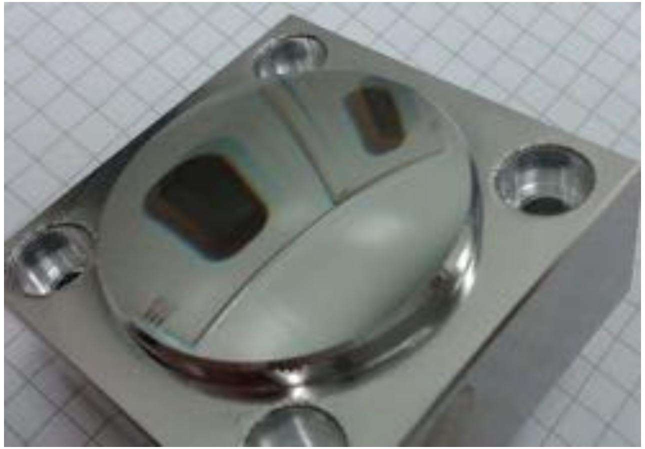
Planning: CHIEM PFM ready by 2020 for In-Orbit Demonstration (GSTP activities)

Freeform Grating Spectrometer Technology

1) Possible to improve and build (compact) Hyperspectral Imager with Freeform (dispersive) optics?

2) Possible to manufacture it?

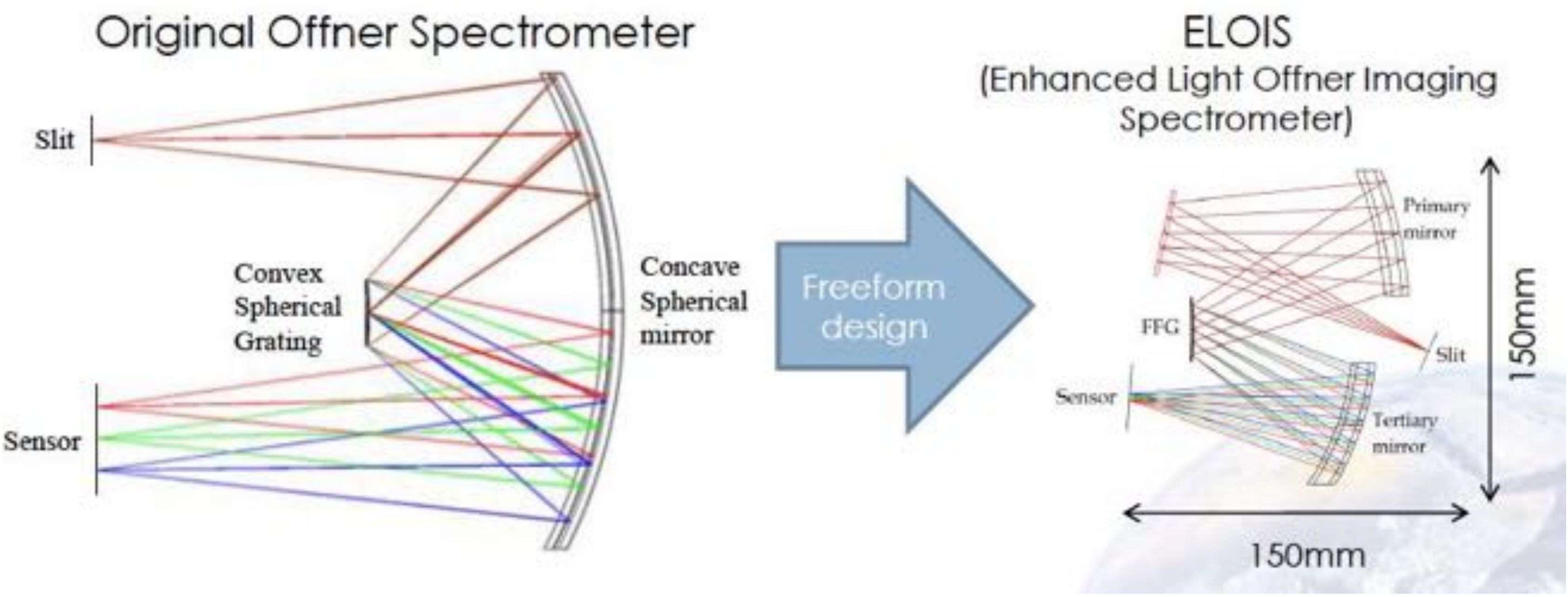
YES



Machined on NiP-plated Aluminum blank with a 4 axis ultra-precision lathe using sharp edge diamond tool.

Grating ruling: 57nm rms SFE

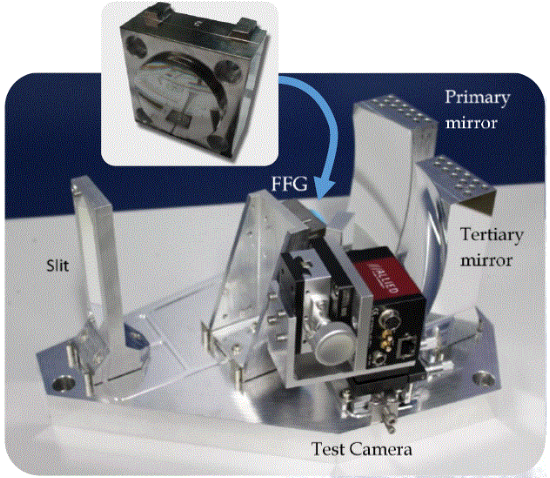
What happens when using freeform optics in a spectrometer



Freeform grating in a spectrometer: ELOIS

Non-symmetrical Offner Imaging spectrometer with demagnification:

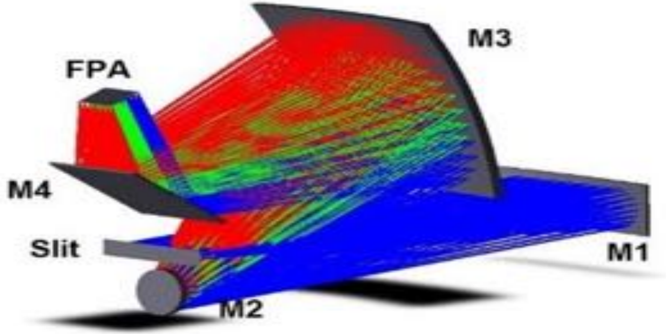
- ✓ All Reflective design with 3 power surfaces
- ✓ **Freeform Ruled grating**
- ✓ Convex **grating with frequency = 104 lp/mm**
- ✓ **Compact design** (150 x 150 mm^2)
- ✓ Longer Slit (=Swath/GSD ratio)
- ✓ Improved SNR



Tests conducted on a functional breadboard.

Hyperspectral for minisat: **CHIMA**

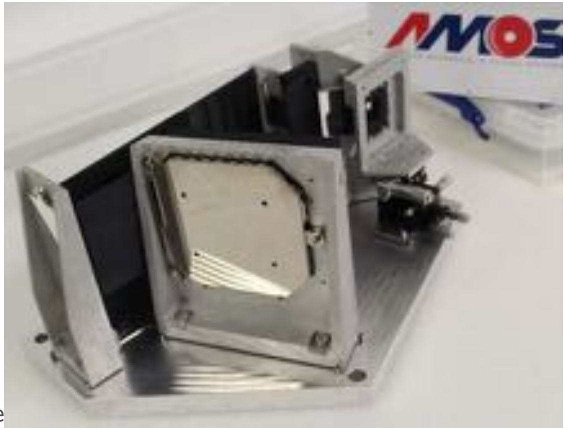
CHIMA: "Compact Hyperspectral Imager for Monitoring Atmosphere" is a Modified Offner Spectrometer:



- All Reflective design with 3 power surfaces
- **Freeform Holographic grating**
- **Grating frequency ~1200 grooves/mm**
- **Compact** (200x200x400 mm)
- Smile corrector with Curved input slit
- Keystone corrector with M4 (Folding mirror)

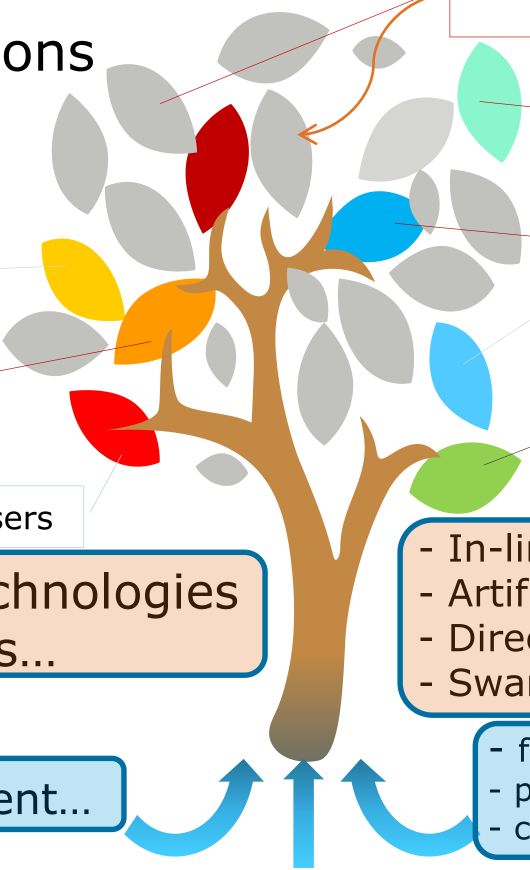
✓ High Spectral Resolution (0.5 nm/3 pixels)
✓ Excellent imaging (MTF > 0.5)
✓ High SNR (> 1000)

CHIMA Breadboard manufactured & assembled:



Technology-push approach

…Disruptive Innovations for Remote Sensing!



???

Biodynamics cultivations (no fertiliser)

Flooding areas delineation

Crop water info

Vegetation parameters (as NDVI) sent to users

Surveillance (eg illegal dumps, camouflage)

Change detection of land cover and land usage

Fire hazard info ready for users

…Game Changer Technologies and Systems…

- In-line processing done on-board up to L2
- Artificial Intelligence
- Direct access to information
- Swarm of satellites (> temporal resolution)

Technologies development…

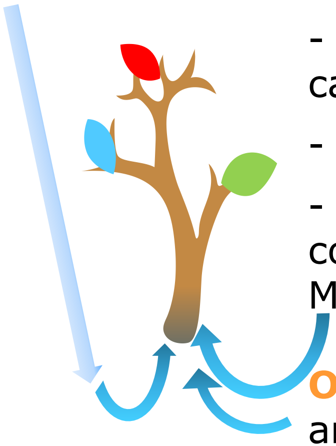
- free form mirrors and gratings
- precision metrology
- compact instruments with CMOS and LVF

What else can we target with compact optical payloads developments?

Atmospheric chemistry!

Dedicated monothematic instruments
(e.g. one instrument per molecule)

Cross info exchange with bigger (eg. Copernicus) satellites



On-board calibration, i.e.:

- miniaturized calibration stimuli for spectro-radiometric calibration (Dutch consortium, led by cosine).

- Absolute radiometric calib. with on-board light source

- Inflight cross calibrations between commercial constellations and institutional (i.e. Sentinel 2) satellites. MATCH activity, contracted to cosine.

On-board use of machine learning (eg. change detection and intelligence also for inflight calibrations).

And more to come…

- Static Fourier Transform Spectrometer: to measure high altitude winds with a cubesat (TRP to be issued)

- MicroMHide: multispectral high definition (i.e. sub-meter) system from microsatellite (GSTP currently running)

Bounced back

Low aspect ratio telescope: a bio-inspired optical system. Game changer for very high resolution from small sat flying at very low altitude.

- Proposed for TRP for Earth Observation and rejected ☹

THANK YOU

Acknowledgements:

ESA: Luca Maresi, Kyriaki Minoglou, Atul Deep, Micael Miranda

cosine: Marco Esposito, Simon Silvio Conticello, Pierluigi Foglia Manzillo, Chris Van Dijk, Nathan Vercruyssen

Medialario: Ivan Ferrario, Massimiliano Rossi, Fabio E. Zocchi, Giovanni Bianucci

VITO: Pieter-Jan Baeck, Iskander Benhadj, Stefan Livens, Bavo Delaure`, Joris Blommaert, Dirk Nuyts

S&T: Michael Soukup, Arnoud Jochemsen, Christina Aas

TU Delft: Ben Gorte, Enayat Hosseini Aria, Massimo Menenti

AMOS: Vincent Moreau, Benoit Borguet, Coralie De Clercq, Jean-François Jamoye

Last but not least: Dutch, Belgian, Norwegian and Italian delegations!

ESA "Optical" Activities (past, present and near future)

HyperCube KO April 2014
End Dec 2015

→ "HyperScout" KO June 2016
Delivery PFM Feb 2017
IOD Flight From Feb 2018

STREEGO KO Oct 2013
End Mid 2016 (+ CCN on 2017)

Direct Deposited Filters (FIDELHEO) KO Jan 2013
End Jan 2015

→ CHIEM KO Jan 2015
End Nov 2017

→ CHIEM-cont KO Sept 2018
End ?Nov 2019

→ CHIEM-PFM KO ?Q2 2019
End ?2020

Feasibility of Free Form Gratings KO Oct 2012
End Nov 2014

→ ELOIS EM KO Nov 2017

→ Free Form Gratings Follow-on (CHIMA) KO Sept 2016
End Q4 2018

Backup: Proba V

MISSION OBJECTIVE:

continuity of SPOT Vegetation data

global daily coverage of land masses (above 35°)

launched in **May 2013**

(lifetime 2,5 years, extension to 5 years)

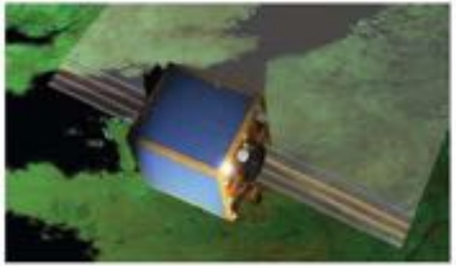
CHARACTERISTICS

like SPOT VGT:
- SWATH width = 2250 km
- 14 near polar orbits per day, @820km
- 4 spectral bands (Blue, Red, NIR, SWIR)

Improvements

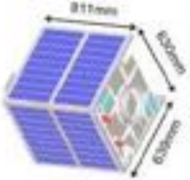
a lot lighter and smaller

spatial resolution:
products: 300m (600m for SWIR)
in addition to 1km like VGT



DIMENSIONS

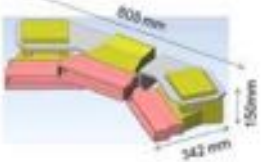
platform



138 kg
Power 150 watt

> 200x smaller
> 20x lighter than SPOT-5 (6m x 3,4 m x 3,1 m, 3000 kg)

imaging instrument



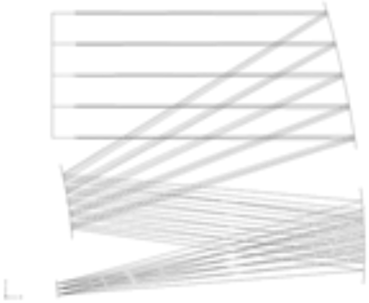
30 kg
Power < 50 watt

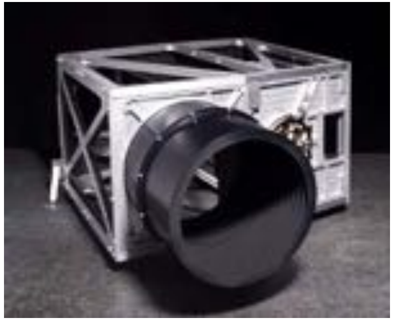
> 17x smaller
> 9 x lighter than SPOT-5 VGT (0,7m X 1 m X 1 m, 160 kg)

An ESA In-Orbit Demonstration, funded through GTSP programme with support of Belgium

Backup: HyperScout and STREEGO

HyperScout™		
Orbit		600 km (300 km)
FoV (ACT x ALT)		31° x 16°
GSD		80 m (40 m)
Swath		350 km (175 km)
Active Resolution		~ 4000 x 2000 px
Spectral range (res)	High res	470 – 900 nm (5 nm)
	Ext. range	400 – 1000 nm (12 nm)
Dynamic range		up to 12 bits
SNR		50 - 100
Mass		1.2 kg
Volume		1.2 L
Avg Power		10 W





STREEGO

Aperture	200 mm
F#	6.0
FOV	1.076° x 0.807°
MTF @ Nyquist	> 64 %
SNR (Pan)	> 100
Mass	19Kg
Volume Envelope	L 541, W 513, H 308 mm
Thermal Control	Passive
Power	48 W

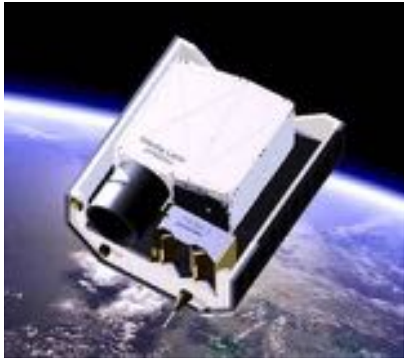
Manufacturing: combination of diamond tuned machining and CNC bonnet polishing on amorphous Nickel-Phosphorous coated Al mirror.

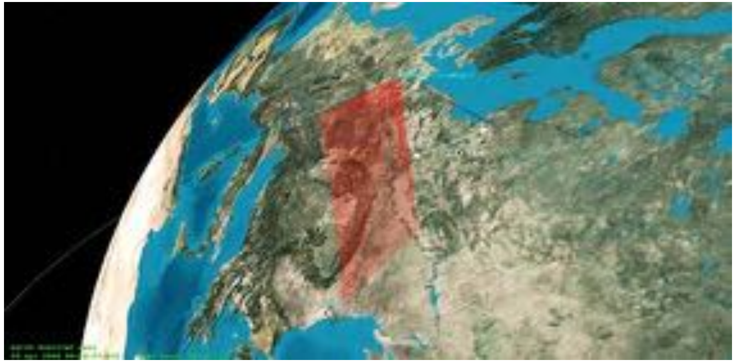
Mirrors: in CTE-matched RSA443 Al, with addition of Silver enhanced coating

Backup: HyperScout + STREEGO = HyperSTREEGO

HyperSTREEGO is an autonomous early warning optical payload system

Combination of high resolution camera (STREEGO) with wide swath looking viewfinder (4 HyperScouts in Panorama layout)





- HyperScout points forward 45° along track, 1 min earlier than STREEGO nadir's coverage
- Panorama spots changes or anomalies in 40 s over a 700 km swath
- Platform re-points STREEGO field of view on anomaly in 20 s
- High resolution multispectral images taken, and transmitted with anomaly warning

Result is a low-bandwidth early detection system, minimizing ground-support cost

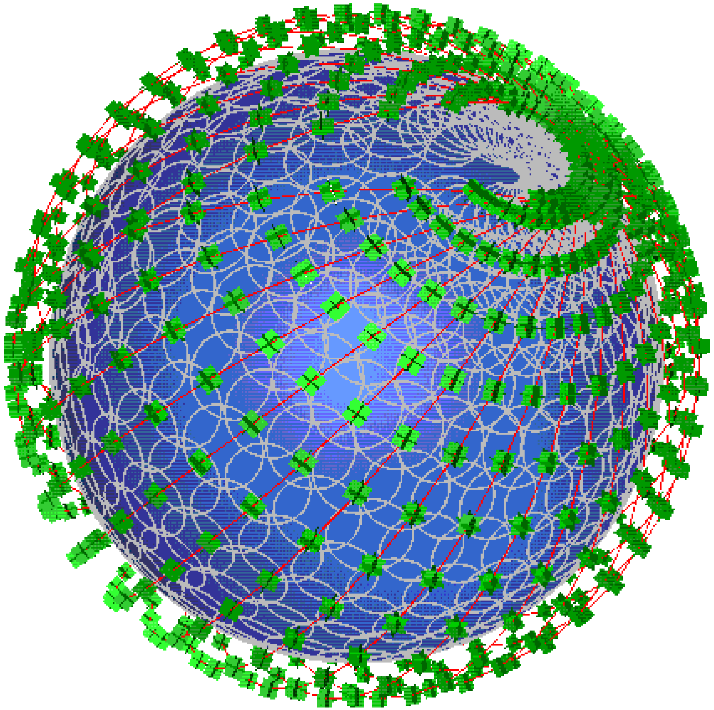
Backup: HyperSTREEGO Constellation?

1) unlimited computing power
2) unlimited memory capacity
3) as many HyperSTREEGOs as you like

Use the H/W in a different way!

not to compress and download data,

but to generate information on board!.



Backup: CHIMA

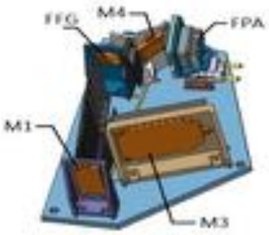
CHIMA BB manufactured & assembled:

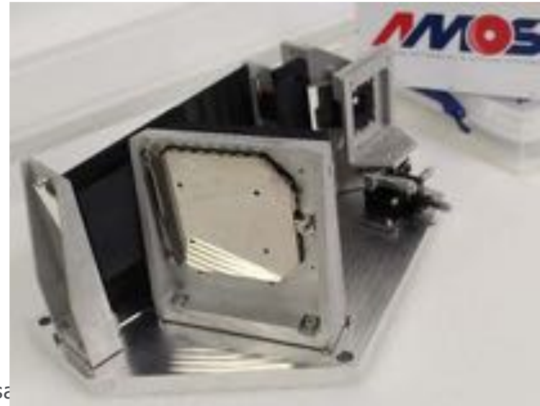
- DT Full aluminium athermal design
- Holographic 1000 gr/mm grating @ HJY
- Curved input slit
- Baffling via Additive Manufacturing

Performance parameter	Value
F-Number	4.05
Effective focal Length	316.958 mm
Stop diameter	21 mm
Slit length x width	60 mm
Slit width	135 µm
Pixel size	15 µm
Spectral resolution	0.56 nm
Spectral sampling	0.19 nm/pixel
Spectral range	600 – 800 nm
Focal plane size (spectral x spatial)	16x20 mm²

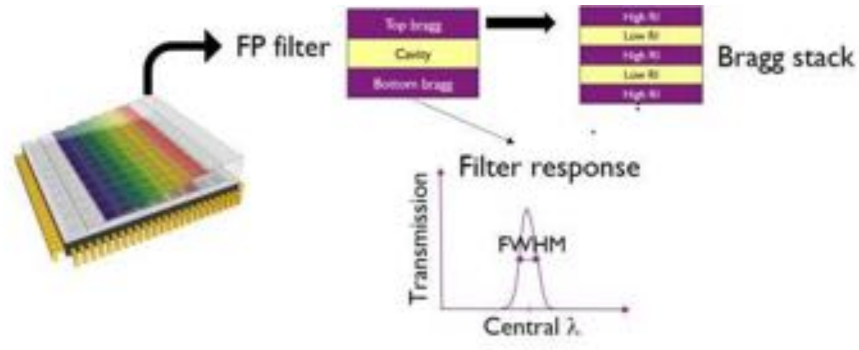
Next Steps:

- Fine optical alignment
- FP Characterization with CSL test-setup (November 2018)





Backup: CHIEM – LVF principles and design



- Filters directly deposited on detector at wafer level, no more alignment issues
- Wedge 1 (470-620 nm) and wedge 2 (600-900 nm) post-processed on top of CMOSIS CMV12000 imager.
- Rejection filters: LP integrated on wedge 1 and HP integrated on wedge 2
- LVF on FSI CMOS and also on BSI CMOS (higher SNR, new development)